Modelling Algal Biological Polishing

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1 Introduction

Ecological modelling is a well established discipline useful in both academic research and industrial resource management. There are two major approaches to ecosystem modelling, which can be described metaphorically as (i) the "top down" approach, and (ii) the "bottom up" approach. In the "top down" approach, a comprehensive and detailed discription of ecosystem components is given, and then interrelated, usually, but not exclusively, in terms of a black box. These models are typically empirical in nature, and specific to a single site. In the "bottom up" approach—the approach adopted in this proposal—a mechanistic mathematical model is constructed. The key inputs, outputs, and internal processes are quantified as functions, and then interrelated through a set of differential equations which represent the dynamics of the system. Typically, this approach aims at understanding the underlying biological/chemical mechanisms at a fundamental level.

The mechanistic modelling procedure is generally organized around the following steps: (a) conceptual and mathematical formulation of the model, (b) numerical solution of the resulting set of differential equations, (c) calibration against field data, and (d) verification starting with an independent set of initial conditions.

In this report a proposal to model two biological processes currently utilized by Boojum Research to remove contaminants from wastewater is forwarded. The first model is for heavy metal bioaccumulation by nonrhizoidal, perphytic algae. This model is based on field data collected by Boojum Research from a decommissioned heavy metal mine at Buchans, Newfoundland. The second model is for radionuclide bioaccumulation by characean algae. This model is based on field data from a decommissioned uranium mine at Rabbit Lake, Saskatchewan. Both models are at an early stage of development, and require further work. In Sec. 2.1 to Sec. 2.5, and Sec. 3.1 to Sec. 3.3 a summary of the current status of the models is presented. Then in Sec. 2.6 and Sec. 3.4 what needs to be done in relation to the modelling procedure given above is listed. The final object is to have biological polishing models which can be used as an aid in planning, design, and management of a decommissioned mine site.

2 Periphyton Biopolishing Model

The periphyton biopolishing model is divided into three conceptual parts:

1. Geochemical equilibrium

2. Periphyton growth

3. Interaction between geochemistry and algae

The main assumption made is that geochemical reaction times are much less than biological reaction times. This certainly holds for the reactor systems Boojum Research works on: characteristic geochemical reaction times are on the order of minutes to hours whereas characteristic biological reaction times are on the order of days to weeks. This allows the computational algorithm to be simplified somewhat, as will be described in more detail below. Before this is done, however, the submodel for the items listed above are summarized.

2.1 Geochemical Reactions

In the literature several different methods for computing chemical equilibria can be found. While they may at first inspection appear unrelated, they can be grouped into two categories: stochiometric algorithms and nonstochiometric algorithms [1]. Stochiometric algorithms incorporate mass balance indirectly, whereas nonstochiometric methods explicitly include mass balance at each integration step. Because it turns out to be more straightforward coupling nonstochiometric algorithms with kinetic models of plant growth, the geochemical submodels are based on these. Nonetheless, because the two methods for computing chemical equilibria are, in fact, equivalent, they are both summarized. Stochiometric routines are based on the following equations:

$$\begin{aligned} \min G(\mathbf{n}) &= \sum_{i=1}^{N_s} n_i \mu_i, \quad n_i \geq 0 \\ \sum_{i=1}^{N_s} a_{ki} n_i &= b_k, \qquad k = 1, \ldots, N_c \end{aligned} \tag{1}$$

Here $G(\mathbf{n})$ is the Gibbs' free energy function, $\mathbf{n} = (n_1, n_2, \ldots, n_{N_s})^T$ is the species vector, μ_i is the chemical potential of species i, (a_{ik}) is the formula matrix, and b_k is the k^th component of the elemental abundance vector. According to chemical thermodynamics, the state $\mathbf{n}$ which minimizes the Gibbs' free energy subject to the mass balance and positivity constraints is the chemical equilibrium state.

In geochemistry instead of minimizing the Gibbs' free energy directly, an equivalent procedure based on equilibrium constants is often employed. In this method chemical equilibrium is expressed in terms of species' concentrations $[A_i] = n_i/V$ where V is the volume of the reactor. The chemical equilibrium state is that one for which the species' concentrations satisfy the following set of nonlinear algebraic equations:

$$\prod_{i=1}^{N_s} [A_i]^{\nu_{ij}} = K_j, \qquad j = 1, \ldots, N_r \tag{2}$$

Here ν_{ij} is the reaction matrix, N_r is the number of linearly indepedent reactions for the system, and K_j are the equilibrium constants corresponding to these chemical reactions.

There are several numerical algorithms available which compute chemical equilibria. In particular, a widely used algorithm to compute geochemical equilibria is PHREEQE, a simulator developed by the U.S. Geological Survey. The theory behind all these algorithms is essentially the same; however, it could be advantageous to use an already existing geochemical simulator rather than code an algorithm from scratch (more will be said on this later).

The polishing ponds engineered by Boojum Research vary in chemical composition. As an example, a set of chemical reactions which obtain for a carbonate system such as the Buchans' polishing ponds are listed:

$$\begin{aligned} CO_{2(aq)} + H_2O &\rightleftharpoons H^+ + HCO_3^- \\ HCO_3^- &\rightleftharpoons H^+ + CO_3^{2-} \\ H_2O &\rightleftharpoons H^+ + OH^- \end{aligned}$$

$$\begin{aligned} ZnCO_{3(s)} &\rightleftharpoons Zn^{2+} + CO_3^{2-} \\ Fe(OH)_{3(s)} &\rightleftharpoons Fe^{3+} + 3OH^- \end{aligned} \tag{3}$$

This set of chemical reactions represents a simplified account of the geochemistry of a carbonate system, but for Buchans it captures the pertinent geochemistry.

2.2 Growth of Periphyton

Boojum Research has pioneered the use of periphyton in removal of heavy metals from wastewaters. To provide a substrate on which the periphyton can grow, alder or spruce branches are placed into mine wastewater treatment ponds. The total amount of algae biomass can, therefore, be quantified in terms of the surface density on the branches, and the total surface area of all the branches. The following equation, which is based in part on widely used phytoplankton growth models [2], is taken as the growth rate equation for periphyton:

$$nA\frac{da_p}{dt} = nA(G_p - D_p)a_p \tag{4}$$

$$\begin{aligned} a_p &= \text{density of periphyton on growth substrate (alder, spruce, etc.)}(kg/m^2) \\ G_p &= \text{growth rate constant}(d^{-1}) \\ D_p &= \text{death rate constant}(d^{-1}) \\ n &= \text{number of trees} \\ A &= \text{surface are per tree which supports periphyton growth}(m^2) \end{aligned} \tag{5}$$

This equation is appropriate for algae which grows in a smooth and continuous fashion on the branches. Field observations suggest that once a critical mass of algae and precipitate form on the branches, the metal laden algae sloughs off abruptly. Eq. 4 still holds for this sort of growth dynamic, but each time a critical density is reached, the density in the following instant must be taken as the initial value (or some minimum density which clings to the branches). In this way a discontinous process can be be modelled using a differential equation:

$$a_p(t) = a_{pmin} \quad \text{if} \quad a_p(t) > a_{pmax} \tag{6}$$

2.2.1 Growth Rate

The rate of periphyton growth depends on four principal components:

1. Temperature, T
2. Solar Radiation, I
3. Nutrients, N
4. PPC (periphyton-precipitate complex) metal concentration, m_a^+

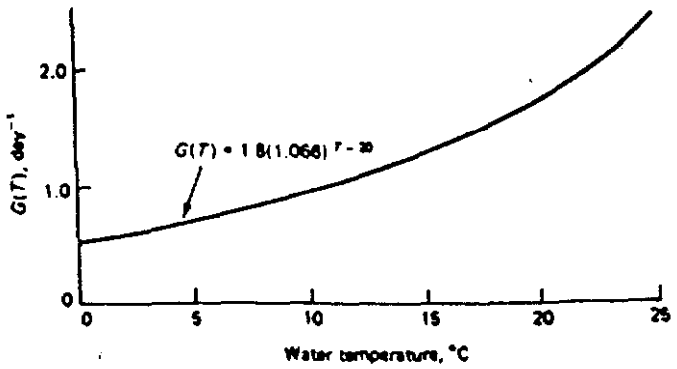


Figure 1: Growth .vs. Temperature (from Chapra and Reckhow)

It is assumed that environmental effects are multiplicative, although there is no *a priori* reason for this. Nevertheless, algal growth models in the literature based on this assumption have been supported by observation [2]:

$$G_p = \mu_{max,20} G(T) G(I) G(N) G(m_a^+) \tag{7}$$

Here $\mu_{max,20}$ is the maximum growth at optimal conditions (nutrient saturation, no metal sorption).

The attenuating functions $G(T)$, $G(I)$, $G(N)$, and $G(m_a^+)$ are taken either from the literature, or determined experimentally under controlled conditions. Below some models are presented for the attenutating functions which have been useful in the study of phytoplankton growth.

1. Temperature Effect. In the case of optimum light, nutrient saturation, and no metal sorption, it has been empirically determined that the growth of algae typically goes as an exponential (see Fig. 1):

$$G(T) = \Theta_\mu^{(T-20)} \tag{8}$$

Here Θ_μ is an empirical constant. The seasonal variation of temperature can be estimated from the meteorological record. In general the growth coefficient is a function of time due to seasonal temperature change, $T = T(t)$.

2. Light Effect. The variation of photosynthesis with light also attenuates growth. There are several models of light attenuation in the literature ranging from Monod-type saturation to exponential growth and decay. For example, the Monod saturation type of factor is (see Fig. 2):

$$G(I) = \frac{I}{K_I + I} \tag{9}$$

Here K_I is the half-saturation constant. The Beer-Lambert Law is used to account for the variation of light intensity over depth in the water column, $I(z) = I_0 \exp(-k_e z)$, (k_e is the extinction coefficient). Also, a photoperiod is used to establish an average daily light intensity. To account for seasonal variation an additional factor is multiplied: $I(t) = I_{avg}[1 + sin(0.008603t)]$ (here t is in days). The pattern of seasonal light variation can be estimated from the meteorological record.

3. Nutrient Effect. This factor couples the growth model to the nutrient model. In our periphyton polishing model, which is based on the Buchans' geochemistry, it is assumed that

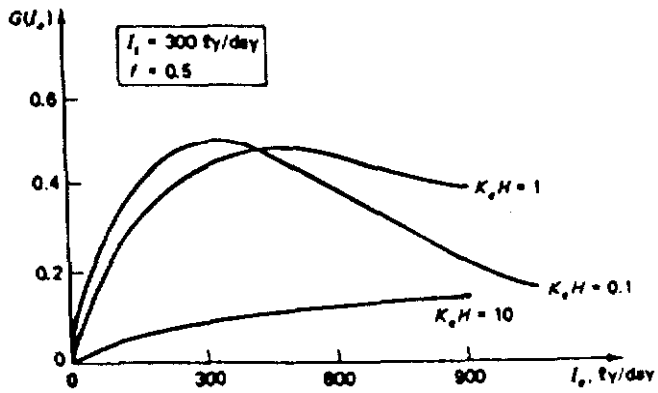


Figure 2: Growth .vs. Light (from Chapra and Reckhow)

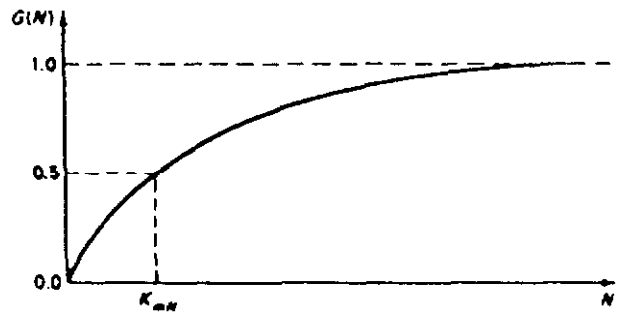


Figure 3: Growth .vs. Nutrient (from Chapra and Reckhow)

carbon is the limiting nutrient, and that CO_2 available to the algae is linked to the carbonate chemistry of the reactor pond. Again, a saturation-type of attenuating factor is assumed (see Fig. 3):

$$G(N) = \frac{N}{K_{mN} + N} \tag{10}$$

Although it is assumed that the limiting nutrient is carbon, the precise carbonate compound available to the algae depends on the pH of the water [5]. A good approximation is:

$$\begin{aligned} N &= [CO_{2(aq)}] \quad \text{if } pH < 5 \\ &= [HCO_3^-] \quad \text{if } 7 < pH < 9 \\ &= [CO_3^{2-}] \quad \text{if } 11 < pH \end{aligned} \tag{11}$$

For intermediate values, the relative proportion of carbonate species available to the algae must be estimated.

4. Effect of Metal Accumulation. The metals bioaccumulated by the algae must ultimately have an effect on the growth of the algae. It is expected that the attenuating function is of the saturation type, or one which limits or even reverses growth (i.e. destroys the plant) above some critical level of contaminant adsorbed by the plants. The relationship between contaminant loading and growth is not known at present.

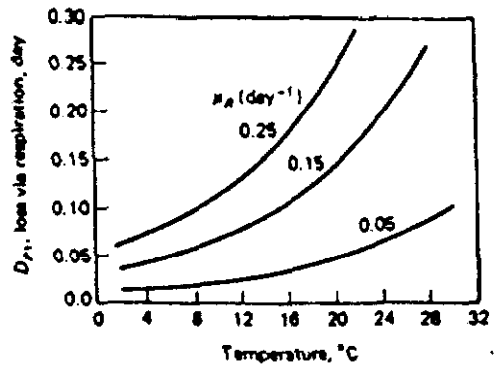


Figure 4: Respiration .vs. Temperature (from Chapra and Reckhow)

2.2.2 Death Rate

The periphyton population does not grow indefinitely. Due to changing environmental factors the balance between growth and death can shift from positive ($G_p - D_p > 0$) to negative ($G_p - D_p < 0$). There are several causes for periphyton loss, reduced temperature and sunlight being the obvious ones. It is assumed that the main source of continuous periphyton loss is due to endogenous respiration in which organic carbon making up the algae is oxidized and excreted to the environment as $CO_{2(aq)}$ and other by-products:

$$D_p = R \tag{12}$$

Here R is the respiration rate of the algae (d^{-1}). It represents the conversion of algal protoplasm into CO_2 and other by-products. There is evidence that respiration depends on light intensity, but the results are not conclusive. Temperature dependence, on the other hand, is well established, and is well described by an exponential (see Fig. 4):

$$R(T) = R_{20}\Theta_R^{(T-20)} \tag{13}$$

Here R_{20} is the respiration rate at $20\,C$, and Θ_R is an empirical constant. The values of R_{20} and Θ_R are found in the literature, or directly measured under controlled conditions.

2.3 Interaction of Geochemistry and Algae

The interaction between the geochemistry and biology can be divided into two parts:

(i) The effect of the geochemistry on algal growth

(ii) The effect of algal excretions on the geochemistry

(i) The geochemistry controls the algal growth through the attenuating factor $G(N)$ discussed above (see Eq.11). Depending on the pH, either $CO_{2(aq)}$, HCO_3^-, or CO_3^{2-} can act as the limiting nutrient. Insofar as chemical equilibrium establishes the pH, the algae growth is also controlled by the pH (although as we discuss shortly, the algae also modifies the pH). Finally, concentration of metal ions in solution control the growth through the attenuating factor $G(m_a^+)$.

(ii) The algae modifies the geochemistry in three principle ways: by bioaccumulating metals, by releasing O_2, CO_2 and other compounds during photosynthesis and respiration, and by altering pH. Bioaccumulation is assumed to follow saturation adsorption. As a first approximation, this can be modelled by Langmuir isotherms. The rate at which the algae removes metals from solution is given as the product of the saturation loading and the algal growth rate:

$$S_M = \frac{nAb[A_M]}{K_{[A_M]} + [A_M]} \frac{da_p}{dt} \tag{14}$$

Here S_M is the removal rate of an aqueous metal species (mgd^{-1}); n is the number of branches or trees; A is the effective growth area per branch/tree; $[A_M]$ the concentration of an aqueous metal species; b ($mgkg^{-1}$) is a constant associated to $[A_M]$; and $\frac{da_p}{dt}$ the rate of algal growth per unit area of substrate.

During photosynthesis and respiration algae releases various compounds to its environment. According to the stochiometry of photosynthesis/respiration, during the synthesis of 1 mg of algal protoplasm 1.31 mg of CO_2 are consumed [2], [3]:

$$S_{CO_2}^{phot} = -1.31nAG_pa_p \tag{15}$$

Here $S_{CO_2}^{phot}$ is the rate at which CO_2 is consumed during photosynthesis (mgd^{-1}), and G_p the growth rate of algae (d^{-1}), as given by Eq. 7.

Similarly, during respiration 1.31 mg of CO_2 is produced per 1 mg of algal protoplasm consumed:

$$S_{CO_2}^{resp} = +1.31nAR(T)a_p \tag{16}$$

Here $S_{CO_2}^{resp}$ is the rate of mass of CO_2 produced during respiration (mgd^{-1}), and $R(T)$ is the respiration rate given in Eq. 12.

The net source/sink of CO_2 due to slow algal biological reactions is then:

$$S_{CO_2} = S_{CO_2}^{phot} + S_{CO_2}^{resp} \tag{17}$$

The influence of algae on pH is also an aspect of algal photosynthesis/respiration. During photosynthesis algae consumes H^+, whereas during respiration algae excretes H^+. The alteration of pH by the algae has the effect of precipitating some aqueous species near the surface of the algae. These processes are typically complex, and as a first step we ignore surface effects. From the stochiometry of photosynthesis/respiration, the following holds [2], [3]:

$$\begin{aligned} S_{H^+} &= S_{H^+}^{phot} + S_{H^+}^{resp} \\ &= -0.005nAG_pa_p + 0.005nARa_p \end{aligned} \tag{18}$$

Here R_{H^+} is the experimentally determined rate of H^+ addition to the system by the algae.

2.4 General Methodology for Combining Fast Geochemical Reactions with Slow Biological Reactions

In this subsection a general methodology due to Di Toro [4] for simplifying mass balance equations is summarized.

The general mass conservation for species A_i *including* fast reactions, and ignoring spatial variation within the reactor is:

$$\frac{d[A_i]}{dt} = S_i + \sum_{j=1}^{N_r} \nu_{ji} R_j + k_{ex}[A_i]_{in} - k_{ex}[A_i], \qquad i = 1, \ldots, N_s \tag{19}$$

Here

$$\begin{aligned} [A_i] &= \text{concentration of species i} \\ N_r &= \text{number of geochemical reactions} \\ k_{ex} &= \text{exchange rate of water} \\ \nu_{ij} &= \text{reaction matrix} \\ S_i &= \text{source/sink of species i due to slow reactions} \\ R_j &= \text{jth reaction producing species i} \end{aligned} \tag{20}$$

It would be desirable to eliminate the fast reaction terms R_j in the above set of equations since typically the reaction constants for these are not known. Even if they are known, they are typically large, and as a consequence the above set of differential equations are "stiff". "Stiff" equations are notoriously unstable and difficult to solve numerically. To avoid these problems the following theorem is useful [4]:

Theorem 2.1 *If the component concentrations are conserved by the reactions then the formula matrix a_{ij} is orthogonal to the reaction matrix: $\sum_{k=1}^{N_s} \nu_{jk} a_{ki} = 0$*

Using this result Eq. 19 can be transformed to a simpler set of equations in which the fast reaction terms R_j are no longer present. Multiply Eq. 19 by the transpose of a_{ij}:

$$\frac{d\sum_{i=1}^{N_s} aik[A_i]}{dt} = \sum_{i=1}^{N_s} a_{ik} S_i + \sum_{j=1}^{N_r} R_j \sum_{i=1}^{N_s} a_{ik}\nu_{ji} + k_{ex} \sum_{i=1}^{N_s} a_{ik}[A_i]_{in} - k_{ex} \sum_{i=1}^{N_s} a_{ik}[A_i] \tag{21}$$

Setting

$$\sum_{i=1}^{N_s} a_{ik}[A_i] = [B_k], \quad k = 1, \ldots, N_c \tag{22}$$

and using Theorem 2.1 gives:

$$\frac{d[B_k]}{dt} = \sum_{i=1}^{N_s} a_{ik} S_i + k_{ex}[B_k]_{in} - k_{ex}[B_k] \qquad k = 1, \ldots, N_c \tag{23}$$

Since the fast reactions are well approximated as being in equilibrium over biological time scales, we can solve the N_r equations in Eq. 2 along with the N_c equations Eq. 22, and N_c equations Eq. 23 for the $N_s + N_c$ unknowns $[A_i]$ and $[B_k]$.

Notice that Eq. 23 includes the slow biological reactions through the source terms S_i.

2.5 Numerical Solutions for Model Equations

The set of equations which model the periphyton polishing pond, and the computational procedure to solve them are listed. The set of equations are:

$$\prod_{i=1}^{N_s}[A_i]^{\nu_{ij}} = K_j, \qquad j = 1, \ldots, N_r \tag{24}$$

$$\sum_{i=1}^{N_s} a_{ik}[A_i] = [B_k], \qquad k = 1, \ldots, N_c \tag{25}$$

$$\frac{d[B_k]}{dt} = \sum_{i=1}^{N_s} S_i + k_{ex}[B_k]_{in} - k_{ex}[B_k] \tag{26}$$

$$\frac{da_p}{dt} = A(G_p(t) - D_p(t))a_p \tag{27}$$

Here $G_p(t)$ and $D_p(t)$ are given by Eq. 7 and Eq. 12 respectively. In addition to these equations the following conditions hold:

$$a_p(t) = a_{pmin} \text{ if } a_p(t) > a_{pmax} \tag{28}$$

$$G(N) = \frac{[CO_2]}{K_{[CO_2]} + [CO_2]} \quad \text{if } -log[H^+] < 3 \tag{29}$$

$$= \frac{[HCO_3^{-1}]}{K_{[HCO_3^{-1}]} + [HCO_3^{-1}]} \quad \text{if } 3 < -log[H^+] < 6 \tag{30}$$

$$= \frac{[CO_3^{2-}]}{K_{[CO_3^{2-}]} + [CO_3^{2-}]} \quad \text{if } 6 < -log[H^+] \tag{31}$$

Qualitatively, the numerical proceedure to solve Eq. 24 through Eq. 31 is as follows. Starting with an estimate of the $[B_k]$ at time step t_0, solve the nonlinear algebraic equations Eq. 24 and Eq. 25 for the $[A_i](t_0)$. Next, with $[B_k](t_0)$, $a_p(t_0)$, $G_p(t_0)$, $D_p(t_0)$, and with $S_i(t_0)$ (dependent upon $[A_i](t_0)$), integrate Eq. 26 and Eq. 27 for $[B_k](t_1)$. Repeat the iteration over the time interval of interest, $t = \{t_0, \ldots, t_f\}$. Note, that at each time step, Eq. 28 through Eq. 31 are tested and satisfied. The end result is the time series of concentrations, $[A_i](t)$ and $[B_k](t)$.

2.6 Milestones

In this section a detailed account is given of what remains to be done to complete the periphyton biopolishing model for the Buchans' site.

2.6.1 Refinement of Conceptual Model

The tentative geochemistry and algal growth proposed in Sec. 2.1 will probably require further elaboration. This will be done in conjuction with model calibration and verification described below. Ecologically modelling is best described as iterative in the sense that initial models are refined by comparing predictions against existing data sets and/or field measurements. The refinement process is in principle on going; however, for the purpose of the initial model ("first

generation model") an additional two to three months of literature review and reading in geochemistry is needed. During this time Buchans' field data will also be re-examined in light of a better understanding of geochemistry.

2.6.2 Numerical Solution of First Generation Model

Using IMSL, a library of numerical algorithms, Eq. 24 to Eq. 31 will be solved. To complete the source code, debug the programs, etc. should take around three months, provided the solutions are numerically stable. If they are not, the numerical aspect of the project could become more difficult, and require longer to sort out.

As mentioned in the section on geochemistry, it may be preferable to solve geochemical equilibria using already existing algorithms, such as PHREEQE, a geochemical simulator prepared by the U.S. Geological Survey. Boojum Research has purchased PHREEQE, and awaits its delivery. Depending upon how complicated an algorithm PHREEQE is, it is estimated to take three months to merge it with the algal kinetic part of the model, and to get the resulting package debugged and running.

2.6.3 Model Calibration

The model must be calibrated against the Boojum data base. Often it is difficult to retrofit a model to a data set which was assembled under different priorities. This is so because not all model variables were necessarily measured, or were measured frequently. Ideally, model building and field programs should proceed concurrently and complementarily. Nonetheless, for the data available calibration should take no longer than two to three months once the computer model is running. The main work here is generating time series of contaminant concentrations from the data base, and comparing them with model time series. If the fit is good, confidence is gained in the model; if it is poor, the model would have to be refined as was commented on above.

2.6.4 Model Verification

The next step is to run the model for conditions different from those at the Buchans' site. If the model is a reasonable one, the output should also be biogeochemically reasonable. This step is very important, since calibration alone might simply be fitting a model to a specific data set without establishing the independent reliability of the model.

2.6.5 Summary

The aim of the final model is to aid in planning, design, and management of ecologically engineered sites. Given the initial contaminant profile and site biogeochemistry, the model will help answer the following basic questions:

(i) How many branches/trees and algal biomass are needed to reduce effluent concentration below some permitted level?

(ii) How much contaminant can be removed by a given crop of algae?

(iii) How does effluent characteristic change over the year?

(iv) How does the site change in response to changes in external controls such as climate, contaminant loading, hydrological flow etc.?

3 Chara Biopolishing Model

A biological polishing model using characean algae is expected to be more complex than that of periphytic algae. The main reason is that chara are rhizoids (algae with roots) which can attach to the sediment and extract nutrients from it. This and other features are discussed below, but first the model is divided into its conceptual parts:

1. Geochemical equilibrium in the water column
2. Geochemical equilibrium in the sediments
3. Algal growth and decay in water column and sediment
    1. chara growth model
    2. nonrhizoidal periphyton growth model
    3. phytoplankton growth model
4. Interaction of geochemistry and algal growth
5. Interaction between chara, periphyton, and phytoplankton

Again, the main assumption made is that geochemical reactions are much more rapid than biological ones such as plant growth and decomposition.

3.1 Geochemical Equilibrium in Water Column and Sediments

The set of equations for the geochemistry of the water column and sediment are similar to those in Eq. 24, 25, and 26:

$$\begin{aligned} \prod_{i=1}^{N_r} [A_i]^{(l)} \nu^{ij} &= K_j^{(l)} \\ \sum_{i=1}^{N_c} a_{ij} [A_i]^{(l)} &= [B_k]^{(l)} \\ \frac{d[B_i]^{(l)}}{dt} &= \sum_{j=1}^{N_c} a_{ij}^{(l)} S_j^{(l)} + k_{ex} [B_i]_{in}^{(l)} - k_{ex} [B_i]^{(l)} \end{aligned} \tag{32}$$

Here the superscript l refers to the submodel: for $l = 1$ Eq. 32 represents the geochemistry of the water column; for $l = 2$ Eq. 32 represents the geochemistry of the sediments. For example, $[A_i]^{(1)}$ is the concentration of species in the water column, whereas $[A_i]^{(2)}$ is the concentration of the

same species in the pore water of the sediment. The other terms are interpreted similarly. The source/sink terms $S_j^{(1)}$ are due to slow reactions in the water column such as adsorption on the algae, and to slow reactions in the sediments whose products are diffused to the water column. It is assumed that pore water originates from the water column so that $k_{ex}^{(2)} = 0$ (i.e. no inflow or outflow from sediment, only diffusion to and from water column). The sources/sinks $S_j^{(2)}$ represent slow reactions within the sediment altering pore water composition, and/or slow reactions in the water column whose products are diffused to the sediment.

3.2 Algal Growth and Decay in Water Column and Sediment

The algal growth model now includes three different species of algae. The same basic form of the growth equation Eq. 4 is taken to describe the growth of chara, nonrhizoid periphyton, and phytoplankton, but the attenuating functions G are modified to account for the different factors which influence the growth of the respective species.

3.2.1 Chara Growth

The growth equation is:

$$A_{bot}\frac{dA_c}{dt} = A_{bot}(G_c - D_c)A_c \tag{33}$$

Here A_c is the density of chara on the lake/pond bottom, and A_{bot} is the area of the bottom. Because established chara colonies are attatched to the sediment, two additional factors influence their growth. First, the nutrients can be got from either the water column, or from the sediment, and therefore the nutrient limitation factor $G(N)$ should reflect this. The following scheme is adopted:

$$G_c(N) = min\{max\{G_c(N_i^{(1)}), G_c(N_i^{(2)})\}\}, \quad i = 1, \ldots, N_n \tag{34}$$

Here N_n is the number of nutrients in the system. Eq. 34 states that the limiting nutrient is the one for which the maximum value of the attentuating function, be it calculated from the water column or sediment pore water water concentration, is smaller than all other such attenuating functions calculated similarly. In this fashion chara are differentiated from the nonrhizoidal periphyton and phytoplankton which can only acquire their nutrients from the water column.

Second, because chara are bottom dwellers, the light they need for photosynthesis can be blocked out by obstacles in the water column. Typically other algae species do this; it is assumed that periphyton and phytoplankton in the water column shade the chara, and thereby limit its growth. To account for this in the chara growth model, we use the Beer-Lambert Law for light attenuation with depth:

$$I(z) = I_0 \exp(-k_e z) \tag{35}$$

Here k_e is the extinction coefficient, which normally depends on the properties of the water. One can think of the shading of periphyton and phytoplankton as a property of the water, so that $k_e = k_e(a_{pavg}, X_P)$, where a_{pavg} is the average density of periphyton in the water column, and X_P is the density of phytoplankton in the water column. It is natural to assume that k_e is a linear

function of a_{pavg} and X_P:

$$k_e = Aa_{pavg} + BX_P \tag{36}$$

The light attenuation function is then given by Eq. 9, but with Eq. 35 and Eq. 36 for I.

3.2.2 Nonrhizoidal Periphyton Growth

The nonrhizoidal periphyton growth model is that given in Eq. 4. Periphyton growth is indirectly connected to sediment geochemistry insofar as processes in the sediment alter the composition of nutrients in the water column. As a first simplification it is assumed that nonrhizoid periphyton are not significantly shaded by other species or by itself (i.e. no self-shading).

3.2.3 Phytoplankton Growth

The phytoplankton growth model is given by:

$$\frac{dX_P}{dt} = (G_P - D_P)X_P \tag{37}$$

Here X_P is the density of phytoplankton in the water column (kgm^3). Phytoplankton draws its nutrients exclusively from the water column, but is, like periphyton, indirectly connected to sediment chemistry *vis à vis* nutrient cycles. Again it is assumed that phytoplankton are not significantly shaded.

3.3 Interaction of Geochemistry and Algal Growth

The geochemistry regulates algae growth in several ways, as was outlined for the periphyton model. First, the nutrient attenuating function $G(N)$ is determined by the quasi-equilibrium concentrations of available nutrients, which themselves are part of nutrient cycles. These cycles are complex biogeochemical processes involving pure geochemistry on the one side, and decomposition of organic matter as well as assimilation by biota on the other. The chara model presented does not include decomposition of organic matter in the sediment. To close the nutrient cycles the plant growth model must be coupled to a decomposition model. In the case of chara, certain nutrients are not only potentially limiting but also potentially inhibiting, even lethal if present in too great concentrations. For example, chara are particularly sensitive to NH_4^+, which is produced in algal decomposition. Finally, pH can have a deliterous effect on plant growth.

3.4 Milestones

In this section a summary is given of what must be done to complete the the tentative Chara biopolishing model for Rabbit Lake outlined above.

3.4.1 Formulation of Model

The work on modelling biopolishing by chara has just been started. Further background reading on chara must be done. Because chara is a rhizoid, the model will have to take into account

sediment chemistry and nutrient cycles. This requires a literature review on sediment chemistry modelling and nutrient cycle modelling. The interaction between various species of algae thought to be important in the growth of chara must also be studied. This require additional background reading and discussion with Boojum personnel who have developed the chara process. Finally the geochemistry of the site especially in relation to the transport and adsorption of radionuclides must be elucidated. The model outlined above is a first sketch, and will be followed by a first generation model. This will take three to four months.

3.4.2 Numerical Solution, Calibration, and Verification

Once the model is properly formulated, the same steps of model building are taken as described in Sec 2. The time taken for these steps should be less than for the periphyton biopolishing model since much of the computational details will overlap. Numerical solutions to the chara model for Rabbit Lake should be at hand by December.

3.4.3 Summary

Given the initial contaminant profile and biogeochemistry of a site, the chara biopolishing model will help answer, among other questions, the following:

(i) How much characean algae is required to lower effluent contaminant concentration below a legislatively required value?

(ii) What is the relation between effluent contaminant concentration and inflow rates?

(iii) How does effluent contaminant concentration change as a result of external changes in climate, loading, etc.?

References

[1] R.W. Missen, and W.R. Smith, *Chemical Reaction Equilibrium Analysis: Theory and Algorithms*, (John Wiley and Sons Inc., 1982).

[2] S.C. Chapra, and K.H. Reckhow, *Engineering Approaches for Lake Management*, (Ann Arbor, MI: Ann Arbor Science Publishers, Inc., 1983)

[3] Stumm, W, and Morgan, J.J., *Aquatic Chemistry*, (New York: Wiley-Interscience).

[4] Di Toro, D.M., "Combining Chemical Equilibrium and Phytoplankton Models-A General Methodology", in *Modelling Biochemical Processes in Aquatic Ecosystems* (Ann. Arbor, MI: Ann Arbor Science Publishers, Inc.), p.233.

[5] F.N. Kemmer, *Water: Universal Solvent*, (Nalco Chemical Company, 1979).

Cost Estimate:

Through the NSERC fellowship $ 25,000 is provided towards the salary of the fellow (item 1 in appendix). His salary has been supplemented by Boojum Research as per job offer (item 5 in appendix) for the first 8 months of the fellowship, to assess the feasibility of the approach. Salary supplement required is $ 600 per month from the CANMET contribution.

Consumables, computer hardware, software, library, photocopy etc, costs of the project are estimated at $ 400 per month. Accessing the Boojum Reseach database requires an estimated 1 day per month Boojum staff * (1 day per month of M. Kalin and 2 days of Martin P. Smith) Martin has worked on each of the field sites collecting data of the polishing ponds.

Details of the cost estimates are given on page 16.

*Curriculum Vitaes attached as item 5.

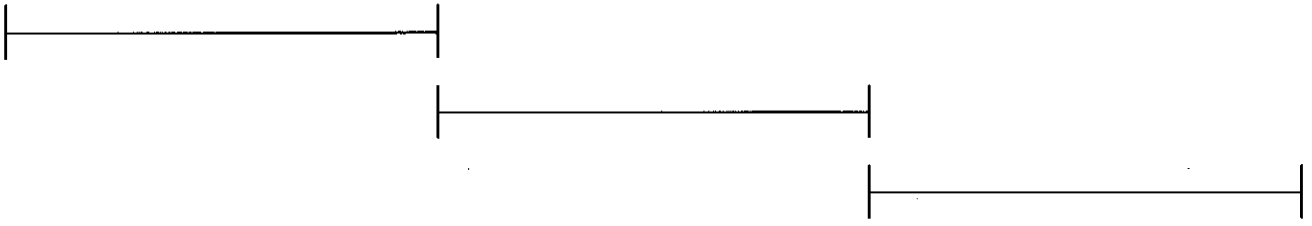
COST ESTIMATE	1994 July	Aug.	Sept.	Oct.	Nov.	Dec.	1995 Jan.	Feb.	Mar.	Totals
NSERC fellow	$2,083.33	$2,083.33	$2,083.33	$2,083.33	$2,083.33	$2,083.33	$2,083.33	$2,083.33	$2,083.33	$18,750.00
(1) Remaining salary	$600.00	$600.00	$600.00	$600.00	$600.00	$600.00	$600.00	$600.00	$600.00	$5,400.00
(2) Consumables	$400.00	$400.00	$400.00	$400.00	$400.00	$400.00	$400.00	$400.00	$400.00	$3,600.00
(3) M. Kalin (1 day/month @ $580/day)	$580.00	$580.00	$580.00	$580.00	$580.00	$580.00	$580.00	$580.00	$580.00	$5,220.00
(4) M.P. Smith (2 days/month @ $440/day	$880.00	$880.00	$880.00	$880.00	$880.00	$880.00	$880.00	$880.00	$880.00	$7,920.00
									TOTAL (Items 1 to 4)	$22,140.00

TIME REQUIREMENTS

Milestone 1
Refinement geochemistry (sec. 2.6.1)

Milestone 2
Integration of PHREEQE (sec. 2.6.2)

Milestone 3
Chara growth habit (sec. 3.4)



APPENDICES

CURRICULUM VITAE

Name: Benjamin Stephen Joseph Romanin

Address: 5396 Braelawn Dr.
N. Burnaby, B.C.
CANADA V5B 2H9

Phone: (604)-298-8920

1. PERSONAL DETAILS

Present Position: Physics instructor
Date of Birth: 1/6/59
Age:34
Sex: Male
Marital Status: Single
Citizenship: Canadian

2. EDUCATIONAL BACKGROUND

1986-1992 Ph.D. mathematical physics
Department of Physics
La Trobe University, Melbourne, Australia

1983-1985 M.Sc. geophysics
Department of Geophysics and Astronomy
University of British Columbia, Vancouver, Canada

1979-1983 B.Sc. Hon. geophysics
Department of Geophysics and Astronomy
University of British Columbia, Vancouver, Canada

3. SCHOLARSHIP AWARDED

La Trobe University Research Scholarship

4. Ph.D. THESIS TOPIC

"The Geometrization of the 2nd Law of Thermodynamics"

In my doctoral dissertation I introduce a completely new microscopic interpretation of the 2nd law of thermodynamics. Rather than invoking some approximation scheme to *derive* macroscopic thermodynamics from microdynamics, I argue that irreversibility is exactly reconcilable with T-invariant microdynamics provided spacetime geometry is enlarged to the noncommutative. I also examine the relativistic symmetry of the Brussels School's "microscopic theory of irreversibility" and conclude it is compatible with the basic tfnets of relativity.

5. M.Sc. THESIS TOPIC

"Cnoidal Waves Generated from a Plasma Instability"

Cnoidal waves are a class of nonlinear waves which arise in a wide variety of physical contexts ranging from hydrodynamics to elementary particle theory. Here I show that an initial perturbation on a two-streaming plasma system can grow into a cnoidal wave rather than saturate into turbulence, which is the standard mechanism for limiting growth of an instability.

6. CONFERENCE PRESENTATIONS

Australian Institute of Physics Conference 1988: Presented a paper on "Electromagnetic Shocks and the Problem of Fast Reconnection" (unpublished)

Australian Institute of Physics Conference 1987: Presented a paper on "Magnetic Reconnection in Plasma Physics, Space Physics, and Astrophysics" (unpublished)

7. PAPERS ACCEPTED AND SUBMITTED FOR PUBLICATION

(i) "Ergodic Theory, Irreversibility, and Relativistic Symmetry"
(accepted by *Physica A*)

(ii) "Lyapounov Variables and the Structure of Space and Time"
(submitted to *Foundations of Physics*)

8. WORK EXPERIENCE

1993	Physics Instructor Kwantlen College Surrey Campus
1989-1990	Lecturer in physics Department of Physics Tasmanian State Institute of Technology University of Tasmania
1985-1989	Demonstrator and tutor Department of Physics La Trobe University
1983-1985	Research assistant in physics Department of Geophysics and Astronomy University of British Columbia
1982-1983	Exploration geophysicist Canadian Superior Oil Inc.

9. INTERESTS

- Swimming, Soccer and Tennis.
- Cinema.

- Languages: English, German, and some French

10. **REFERENCES**

- Professor Ilya Prigogine
  Code Postal 231—Campus Plaine U.L.B.
  Boulevard du Triomphe—1050 Bruxelles, BELGIUM
  Tél. (02) 640 00 15, ext: 5540

- Professor Keith D. Cole
  Department of Physics
  La Trobe University
  Bundoora, Vic. 3083, AUSTRALIA
  Phone: (61)-(3)-479-2735

- Professor Don Russell
  Department of Geophysics and Astronomy
  University of British Columbia
  2219 Main Mall
  Vancouver, B.C. V6T 1Z4, CANADA
  Phone: (604)-822-2551

Natural Sciences and Engineering Research Council of Canada
200 Kent Street
Ottawa, Canada
K1A 1H5
Facsimile: (613) 992-5337

Conseil de recherches en sciences naturelles et en génie du Canada
200, rue Kent
Ottawa, Canada
K1A 1H5
Télécopieur: (613) 992-5337

INDUSTRIAL RESEARCH FELLOWSHIP

(This form is to be completed <u>after</u> the fellow has arrived to take up the award at the host organization).

NAME OF FELLOW ....Ben....Romanin.....

SPONSORING COMPANY ..Boojum....Research.....

HOME ADDRESS ...(as...above.).....400 Queen...St...E....
.....Suite 400
.....Toronto...Ont.....
M5A 1T7

TELEPHONE NUMBER (home) .....

(work) (416).-..861.-.1086

I accept the NSERC industrial research fellowship. The official starting date of this award is ....November...3.,..1993....

SOCIAL INSURANCE NUMBER 717..-357.-.156
(required by NSERC for payment purpose)

ANNUAL SALARY $..32,000..

...Ben...Romanin.....
Signature of fellow

.....
Signature of Authorized Company Official

Canada

Natural Sciences and Engineering Research Council of Canada
Scholarships and International Programs
350 Albert Street
Ottawa, Canada
K1A 1H5
Facsimile: (613) 996-2589

Conseil de recherches en sciences naturelles et en génie du Canada
Bourses et programmes internationaux
350, rue Albert
Ottawa, Canada
K1A 1H5
Télécopieur: (613) 996-2589

800
October 20, 1993

Dr. Margarete Kalin
President
Boojum Research Limited
468 Queen Street East
Suite 400, Box 19
Toronto, Ontario
M5A 1T7

Dear Dr. Kalin:

I am pleased to inform you that Dr. Benjamin Romanin has been a successful candidate in the most recent competition for an Industrial Research Fellowship. By separate letter he has been advised of the award and is being asked to confirm acceptance of the fellowship and the expected reporting date.

Enclosed is a copy of the Scholarships and Fellowships Guide. I refer you to paragraph 197 regarding the commencement date of the fellowship. This paragraph states that the fellowship must normally be taken up within three months of this notification of decision. In exceptional cases, and where agreed to by the company at the time of nomination and indicated in the Offer of Employment section of form 217, the award may be taken up within six months of approval of the fellowship.

Industrial Research Fellowships are valid for a maximum period of two years. Fellows must be involved in one, or at most two, challenging projects as described in the nomination documentation. These projects should provide the fellow with an opportunity to grow professionally. However, it is understood that it may be necessary from time to time to assign the fellow to special projects of a temporary nature; such short-term projects **must not** consume more than 20% of the fellow's time. While we realize that it may occasionally be necessary to make major changes to the program of research, this should happen only in very exceptional circumstances. Companies should notify NSERC immediately of any such departure during the tenure of the fellowship, providing a letter justifying the change and a revised description of the work to assist us in monitoring the results of the fellowship.

A progress report, to be completed either by the fellow or the supervisor using the attached form, is required at least two weeks prior to the end of the first year of the award. Also, a brief final report must be provided within six months of the expiration of the fellow's appointment (see paragraph 205 of the Scholarships and Fellowships Guide).

.../2

NSERC's contribution to the fellow's salary and fringe benefits now stands at $25,000 annually. Please note that in any situation where an industrial research fellow is involved in contracts, no double billing should occur. That is, only the portion of the fellow's salary over and above NSERC's contribution should be claimed under the contract.

In order to recover NSERC's contribution to the fellow's salary, please forward to our office, **at the end of each four-month period of tenure, an invoice which has been certified by an authorized company official.** These invoices should cover four complete months from the fellow's actual starting date (e.g. for an award taken up on July 15, the first invoice should cover the four months ending November 14). Our contribution will be paid as follows: 1st instalment - $8,269.23; 2nd instalment - $8,365.38; and 3rd instalment - $8,365.39. Please do not bill us for partial periods unless the fellowship has been terminated. Your invoice should include the fellow's name, the period of time for which payment is requested, the amount claimed and our file reference-IRF800.

When your successful candidate arrives to begin tenure of the fellowship, I would ask you to please advise NSERC, using the attached form; this should be sent to Ms. Pat Houston, the Industrial Research Fellowships Officer. Should you have any questions, please do not hesitate to contact Ms. Houston at (613) 996-2009.

Yours sincerely,

Teresa Brychcy
Director,
Scholarships & Fellowships
Programs

TB/ld
Encl.

MEMORANDUM OF AGREEMENT

BETWEEN:

BOOJUM RESEARCH LIMITED
(hereinafter referred to as "Boojum")
OF THE FIRST PART

- and -

BENJAMIN STEPHEN JOSEPH ROMANIN
(hereinafter referred to as "Ben")
OF THE SECOND PART

WHEREAS Boojum employs Ben as a Research Associate on a full time basis.

THIS AGREEMENT WITNESSETH and the parties hereto shall be governed by the following covenants:

1. Commencing October 1, 1993, and contingent upon receipt of NSERC fellowship, Boojum will pay to Ben the sum of THIRTY TWO THOUSAND DOLLARS ($32,000.00) annually less the necessary deductions for income tax, Unemployment Insurance and Canada Pension and whatever contribution he is required to make to a benefit plan or plans instituted by Boojum from time to time for employees' benefits.

2. Ben will enjoy those company benefits available to Boojum's employees.

3. Ben will be entitled to a 2 week paid vacation each year. Ben will advise the Personnel Administrator of his holiday plans sufficiently in advance of taking same, so that all company matters are arranged to be attended to during his absence.

4. Ben acknowledges that the terms of this Employment Contract and the Confidentiality Agreement executed by him constitute the full agreement between the parties. The parties hereto understand and agree that the breach of any of the terms of the above-mentioned agreements constitute reason for immediate dismissal, without remuneration, of Ben by Boojum. Ben understands and agrees that it is mandatory that he have no conversations about his work or that of any employee or representative, and that any breach of this strict confidentiality is immediate grounds for his dismissal by Boojum.

EACH OF THE TERMS OF THE WITHIN AGREEMENT IS SEVERABLE, and the invalidity of any one of the terms hereto does not render the entire agreement null and void.

IN WITNESS WHEREOF the parties hereto have hereunto set their hands and seals this first day of September, 1993.

BOOJUM RESEARCH LIMITED

per: _____

_____

Benjamin S.J. Romanin

Natural Sciences and Engineering Research Council of Canada

Conseil de recherches en sciences naturelles et en génie du Canada

INDUSTRIAL RESEARCH FELLOWSHIP

PROGRESS REPORT

NAME OF FELLOW: Dr. Ben Romanin

NAME OF COMPANY: Boojum Research

R&D PROJECT/ACTIVITIES

Has the fellow been working on the project/activities outlined by the company in the original proposal? Yes X No ____

If there have been any significant changes in the project objectives and/or content, please give the reasons why the changes were made:

There have been no significant shifts in project objectives and/or content, but there has been a shift in focus. The original proposal was to mathematically model the entire ARUM treatment system including alkalinity generation from decomposing organic matter and bioaccumulation of heavy metals on cattail roots and periphyton algae. Because of the complexity of the system it was decided that a more realistic approach would be to model the components separately. In this vein, the first component to be modelled is biological polishing by periphyton algae.

Briefly describe the major research and development activities undertaken:

I. Constructing Conceptual Biogeochemical Models

Conceptual models are constructed based on the following processes:
(i) Growth of periphyton algae
(ii) Metal accumulation by algae
(iii) Geochemistry of heavy metal precipitation
(iv) Interaction between algal growth and metal bioaccumulation
(v) Interaction between geochemistry and algal bioaccumulation

II. Generating Numerical Solutions of Mathematical Models

Solving the mathematical model numerically. The model is quantified by a system of differential equations which can only be solved numerically on a computer.

Progress to date:

I. Conceptual Models

To date a prototype model of algae growth and metal bioaccumulation has been constructed. The model is a first attempt to quantify (i), (ii), and (iv) above. The chief problem has been quantifying bioaccumulation. In particular, the kinetics of metal bioaccumulation on algae is not well documented in the literature. The Boojum data base does provide growth rates of algae in polishing ponds, but the precise relation between growth and bioaccumulation is not yet fully quantified.

The open questions in the preliminary conceptual model are:
a. Is bioaccumulation of heavy metals describable by local equilibrium Langmuir adsorption isotherms? Or is the bioaccumulation kinetic on time scales of geochemical reactions?
b. How does metal loading on algae effect the growth rate of the algae?

A more detailed conceptual model of biological polishing would include the crucial interplay between geochemistry, algae growth, and bioaccumulation ((i) to (v) above). Once the preliminary model is numerically solved and calibrated, a more detailed biological polishing model incorporating these processes will be constructed.

II. Numerical Solutions

Arrangements have been made to access a minicomputer to solve the system of differential equations which quantify the conceptual model. To date network connection problems have hampered progess; however, some simple test runs have been completed, and once the computing work station is emplaced numerical solutions of the preliminary biological polishing model can be generated. A Runge-Kutta fifth order numerical routine is used, but requires some modification to accept differential equations with time-dependent coefficients. If the system of differential equations proves stiff, an Adams-Moulton, or Grear numerical routine will be used.

Signature of fellow

Signature of supervisor

Please return this form to:

Ms. Pat Houston
Industrial Research Fellowships Officer
NSERC
200 Kent Street Ottawa, Ontario K1A 1H5

CURRICULUM VITAE

Margarete Maria Kalin

Margarete founded the company and pioneered the application of Ecological Engineering and Biological Polishing to the mining industry. Since 1978, she has worked on the ecology of uranium tailings sites in Canada, and expanded her work to include base metal and coal mine sites in both Canada and the U.S. Margarete has written and co-authored numerous publications detailing her research.

EDUCATION

1964	Ecole Benedict, Bienne, Switzerland, Commercial Diploma
1965-1969	Agricultural Biochemical Technologist, Geigy Ltd., Basel, Switzerland
1970-1971	University of Waterloo
1972-1974	University of Toronto, B.Sc. (Biology)
1975-1977	University of Toronto, M.Sc. (Entomology)

PROFESSIONAL EXPERIENCE

1993- Adjunct Professor, **Department of Geological and Mineral Engineering, University of Toronto**, Ontario.

1982- Research Director and President of **Boojum Research Limited.** Management of the company and Principal Investigator of all contracts related to Ecological Engineering and Biological Polishing.

1977-1984 **University of Toronto, Institute for Environmental Studies**
Research Associate and Principal Investigator of all university contracts. Research on uranium mill tailings, chemical and ecological characteristics, and long-term rehabilitation of the waste sites.

1974-1977 **University of Toronto, Department of Zoology**
Graduate Student, Research and Teaching Assistant, and Laboratory Technician (part-time).
Research in social entomology, glandular development in Heteroptera by scanning electron microscopy, and reproductive biology in mice.

1973-1974 **University of Waterloo, Departments of Biology and Earth Sciences**
Student and Research Assistant.
Research on fossil insects in arctic soils, identification of insect fractions.

1972-1973 **McGill University, Department of Biology**
Research Assistant.
Department of Biochemistry
Laboratory Technician (part-time). Genetics of *Aspergillus* sp. and research on enzyme kinetics.

1969-1972 **University of Zurich, Switzerland, Department of Zoology**
Laboratory Technician. Research on neuro-physiology of insect vision, desert ants and bees.

Swiss Federal Institute of Technology, Zurich, Switzerland, Department of Zoology Laboratory Technician. Research on repair mechanisms in X chromosomes of *Drosophila melanogaster.*

PUBLICATIONS

Refereed Journals
1971 - 1991 Senior or sole author - 6
Junior author - 2

Conference Proceedings
1981 - 1994 Senior or sole author - 42
Junior author - 13

Contract Reports at University of Toronto
1978 - 1986 Senior or sole author - 35
Junior author - 5

Book Chapters
1988 - Senior author
1989 - Sole author

MEMBERSHIPS AND ASSOCIATIONS

American Association for the Advancement of Science
American Society for Surface Mining and Reclamation
American Society for Testing and Materials
BIOMINET
BIOQUAL
Canadian Association on Water Pollution Research & Control (CAWPRC)
Canadian Institute of Mining and Metallurgy
Canadian Land Reclamation Association - Presently serves as President
Canadian Mineral Processors (CMP)
Canadian Nuclear Society

National Biotechnology Advisory Committee
Reclamation Technology (RECTEC)
Society for Ecological Restoration (SERM)
Soil and Water Conservation Society

PUBLIC RELATIONS ACTIVITIES

Television interviews regarding Ecological Engineering on Global News (1992) and CBC Newshour (1993).

House of Commons Standing Committee on Energy Mines and Resources, guest speaker for "Sustainable Energy and Mineral Development: A Realistic Response to the Environmental Challenges", Minutes of the Proceedings of the House of Commons, Wednesday November 6, 1991.

Radio interviews on CBC-LaRonge, regarding Uranium City work during 1981 and 1982. "Low-level radwaste disposal opinions sought." ECO/LOG, Volume 10, No. 6, February 19, 1982. "Uranium waste a growing problem."

IAEA served as Canadian Observer and Chairman of Workshop Session on Radium and Uranium Tailings, Rio de Janeiro, February, 1984. IAEA served as Canadian Observer for Workshop in Ottawa, Ontario, May 17-21, 1982.

Resides on Editorial Board for The Journal of Ecotechnology, Elsevier Science Publishers, N.Y.N.Y.

VHS Video Documentary on Ecological Engineering, sponsored by CANMET.

President Canadian Land Reclamation Association (CLRA)

Appointed to the National Biotechnology Advisory Council (NBAC) 1992.

Appointed as Expert on Ecological Engineering by the World Bank.

T.V. Ontario interview for Live International Videoconference "The Environmental Biotechnology Story" Toronto, May 1994

CJRT-FM interview "Ecological Engineering", April 1994

NEWSPAPER ARTICLES

"Company bugs mine waste dumps," by Andrew Timble in The Toronto Star, Aug. 10, 1993, pp. B1 & B2.

"Tailings Sites Revisited," by Dorothy Parshall in The Bancroft Times, Aug. 24, 1993, Vol. 99 (34), p. 11.

"In Search of a Solution" in Canadian Mining Journal, Tailings Tips feature, Fall Issue, 1991. Repeated in Mine Waste Management News, Vol 2 #4, October 1992.

MITEC Newsletter, Vol. 3, No. 4, April 1991. Boojum Research Limited is Feature Organization.

"Mining with Microbes," by Keith Debus in Technology Review, August/September 1990, published by MIT, Massachusetts.

"Tailings management: A long-term problem?" CNS Bulletin, January/February 1984.
"Biologist advises working with nature in abandoned uranium mill tailings." Nuclear Fuels, December 5, 1983.

"ICP Users." Bulletin, July 25, 1983.

Toronto Sunday Star, Perspective, December 19, 1982.

"Ecological Engineering Viewed as a Means to Manage Mining Wastes", in HazTECH News, March 1993, Vol. 8, (5), p.36.

LECTURES AND COURSES

University of Toronto, 1989, Division of Geo-engineering, Guest Lecturer for the Geological and Mineral Engineering Program.

McGill University, 1991, Department of Mining and Metallurgical Engineering, Guest lecturer, "Professional Development Seminar on Water in Mineral Processing".

CIM, 1991, taught course "Mining and the Environment". Course was offered at Vancouver, B.C. and Red Lake, Ontario.

Logan Club, Geological Survey of Canada Lecture Series, February 3, 1993, "Ecological Engineering; Life After the Death of a Mine".

University of Toronto, 1994, Department of Geological and Mineral Engineering, undergraduate Ecological Engineering Course (GEO430S).

BC Biotechnology Alliance, February Distinguished Speaker (1994), Vancouver, BC. "Ecotechnology in Mining and Bioremediation."

Toronto Biotechnology Initiative, Biotech Breakfast Guest Speaker, March 17, 1994. "Ecological Engineering: Biotech and the Environment."

McGill University, Student Chapter Guest Speaker, March 11, 1994.
"Ecological Engineering: Management and treatment of industrial water."

CURRICULUM VITAE

Martin Patrick Smith

EDUCATION

1978-1982 University of Toronto, B.Sc. (Botany)

1984-1987 University of Toronto, M.Sc. (Botany)
Thesis: Phosphorus nutrition of Chara vulgaris
Dept. of Botany, University of Toronto.

WORK EXPERIENCE

March 1991 PresentVice President of Operations, Boojum Research Limited
Co-ordinator of all projects and field work

1984-1991 Research Associate, Boojum Research Ltd.
Development of Biological Polishing and Ecological Engineering Methodologies for waste managment areas in the mining sector. Development of "The Chara Process".
-field investigations of the autecology of Characean populations
-field and laboratory investigations of the environmental tolerance of, and contaminant sorbtion by, the Characeae in uranium, gold, nickel, zinc, copper and aluminum tailings effluents
-Development of substrate interstitial solution chemistry sampling techniques
Ecological Engineering
-field investigations during feasibility studies in Ontario, Northwest Territories and Nova Scotia at uranium, gold, nickel and copper mining operations

1985-1987 Teaching Assistant, University of Toronto.
-Morphology and Evolution of Plants

1983-1984 Technician, Institute for Environmental Studies, University of Toronto
-Aging of aspen and birch populating stressed environments
-Neutron activation analysis
-Programming: PLI, SAS
-Scientific drafting
-Literature review and editorial work, under supervision of M. Kalin, Institute for Environmental Studies, U. of Toronto

1983 Laboratory Technician, Dept. of Botany, University of Toronto
-Processing vegetation samples collected on Ellesmere Island, N.W.T. under the supervision of Dr. J. Svoboda, Dept. of Botany

1982 Field Technician, Dept. of Botany, University of Toronto
-Feasibility study of high arctic agriculture
-Phenology of four tundra perennials
-Manipulations of growth factors in a high arctic wet sedge meadow, within the ecological study of a high arctic oasis, Alexandra Fjord, Ellesmere Island, N.W.T., under the supervision of Dr. J. Svoboda, Dept. of Botany

1981 Field Technician, Dept. of Botany, University of Toronto
-Quantification of ground species over growth season in a Carolinian forest, under the supervision of Dr. T.J. Carleton, Dept. of Botany

CONFERENCE PROCEEDINGS

1991 Kalin, M. and M.P. Smith, "Biological amelioration of acidic seepage streams. "Proceedings of the Second International Conference on the Abatement of Acidic Drain 1991, pp. 355-368.

1989 Smith, M.P. and M. Kalin, "Biological Polishing of Mining Waste Waters: Bioaccumulation by the Characeae." Proceedings of the 1989 Biohydrometallurgy Conference, Jackson Hole, Wyoming, August 13-18, 1989.

1989 Kalin, M., M.P. Smith and R.O. van Everdingen, "Ecological engineering measures developed for acid generating waste from a copper/zinc concentrator in Northern Ontario." Proceedings of the Conference "Reclamation, A Global Perspective," Calgary, Alberta, August 27-31, 1989, pp. 661-672.

1988 Kalin, M. and M.P. Smith, "Biological polishing: The Chara Process." Proceedings of the 13th CLRA Convention, Ottawa, Ontario, August 7-10, 1988, pp. 87-95.

1988 Vandergaast, G., B. Phillips, M. Kalin and M. Smith,"Application of ecological engineering at a uranium mining facility in northern Saskatchewan." Proceedings of the International Symposium on Uranium and Electricity: The Complete Nuclear Fuel Cycle, Sponsored by The Canadian Nuclear Society, Saskatoon, Canada, 1988.

1986 Kalin, M. and M.P. Smith, "Ra 226 and Pb 210 concentration ratios in terrestrial and wetland plants on inactive and abandoned uranium mill tailings in Canada." Canadian Nuclear Society, 7th Annual Conference, Toronto, Ontario, June 9-10, 1986, pp. C9-C10.

1985 Kalin, M. and M.P. Smith, "Establishment of pioneering trees on an inactive uranium tailing site in Elliot Lake, Ontario." Proceedings of the 10th Annual Meeting Environment and Reclamation: Ten Years of Achievements, CLRA, Quebec, August 18-21, 1985, pp. 102-118.

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Biological Polishing

An application model for alkaline, neutral and acidic waste water

Project Overview

Based on a feasibility study in 1989 the use of an attached growing algae, Chara, to remove Ra 226 in alkaline effluents of an uranium mine in northern Saskatchewan was tested. Four growing seasons later, the transplanted algae remove 65 % of the annual Ra 226 loading from the upper part of the drainage basin. The development of the Chara process, designing criteria and quantification of the treatment capacity were supported by CAMECO and CANMET Biotechnology.

Attached growing algae, Ulothrix sp or Ocsillatoria sp, are used as polishing agents in neutral or acidic water to remove Zn and other metals. The metal removal mechanisms , design criteria for the use of the biological polishing process and expected performance have been determined.

The process has been scaled up for neutral effluents for zinc removal based on design criteria developed to date with the support by Asarco and CANMET biotechnology. Biopolishing for acidic waste waters is utilized at a abandoned mine site in northern Ontario. The quantification and scale up for the appplication to those waste waters is supported also jointly supported by Canmet with Talisman Energy Inc.

These applications have produced a large data set for biological polishing. These data could be used to verify a mathematical application model. With a model at hand which incorporates growth of algae and geochemical behaviour of the waste water the technology could then be used by industry to assess the application of the process.

An industrial post doctoral fellowship was granted to Dr. Ben Romanin (CV in appendix item 1) by NSERC (letter of approval and acceptance item 2 in the appendix). A conceptual model has been developed since the beginning of his fellowship at Boojum Research Limited. The overall framework for Ecological modelling is provided in the Appendix (item 3) along with the first progress report after 4 months of tenure (item 4).

The enclosed proposal, summarizing the status after 8 months of work " Modelling Algal Biological Polishing" outlines the work requirements for the coming 9 months, covering the period of July 1994 to March 31 1995. Milestones are described in section 2.6.1 Refinement of conceptual model and literature review on geochemistry; In section 2.6.2 Integration of PHREEQE, debugging and source code merging with growth model developed to date as contained in the proposal; in section 3.4 it is proposed to add the Chara process growth habit to add to the biological model.

With this proposal, support is requested for the remaining fiscal year, 9 months, to cover the

contribution required for the post-doctoral fellowship through Boojum Research.
With the requested funds of $22,140 as per cost estimate given on page 15 of the proposal, biological polishing processes would be ready for application in industry through the use of the model, based on performance data of field demonstrations.

Once the model is brought to the application stage by March 1995 testing of the model is being discussed with industry, using data from sites, where the application of the biological polishing process could be considered. Funding for 1995 is expected from industry.